FIBRESHIP
INTEGRAL COMPOSITE SHIP

This project has received funding from European Union´s Horizon 2020 research and innovation programme under grant agreement Nº 723360

Materials for large length fibre-based ships. Characterization, selection, and numerical analysis

Participants: CIMNE, COMPASSIS, ULIM, VTT, TWI, LR, BV, RINA, TUCO, IXBLUE, TSI

Madrid, October 1th 2019

INTRODUCTION

We need to know:

- The performance of the material (characterization)
- Numerical tools to help engineers in the structural design

BRIEF DESCRIPTION

SELECTION OF COMPOSITE MATERIALS FOR MARINE APPLICATIONS

- Testing campaign – 1st phase
- Selection criteria
- Testing campaign – 2nd phase
- Fire performance

CHARACTERIZATION AND SIMULATION OF FIBRE-BASED MATERIALS

- Model to analyze the mechanical performance of composites
- Calibration process and numerical results
- Fatigue Analysis

FIBRESHIP
INTEGRAL COMPOSITE SHIP

SELECTION OF COMPOSITE MATERIALS FOR MARINE APPLICATIONS

CHALLENGE AND APPROACH

- Identification of new fibre based material systems for large scale vessels is a key objective of Fibreship
- Comprehensive list of candidate constituents

Phase 1 → Phase 2

Extensive small scale experimental campaign to down-select the best resin candidates

Selection of reinforcement material and detailed characterization of the best composite candidates for Fibreship application

PHASE 1 – MATRIX CANDIDATES – Mechanical Properties – All tested with GLASS FIBRES

RESIN CLASS	RESIN/REINFORCEMENT	v_f (FIBRE VOLUME FRACTION)	DENSITY	APPARENT INTERLAMINAR SHEAR STRENGTH	FLEXURAL STRENGTH	FLEXURAL MODULUS	Resin Cost[3] (€ per kg)	Resin/Hardener Mixture Cost[3] (€ per kg)
VINYLESTER	LEO SYSTEM/ LEO UD 940gsm Glass							
URETHANE ACRYLATE	CRESTAPOL 1210/ UD 996gsm Glass[2]							
EPOXY	PRIME 27/ UD 996gsm Glass[2]							
	SR1125/ UD 996gsm Glass[2]							
BIO-EPOXY	SUPER SAP CLR/ UD 996gsm Glass[2]							
PHENOLIC	CELLOBOND J2027X/ UD 996gsm Glass[2]							
THERMOPLASTIC	ELIUM/ UD 996gsm Glass[2]							

PHASE 1 – MATRIX CANDIDATES – Mechanical Properties – All tested with GLASS FIBRES

RESIN CLASS	RESIN/REINFORCEMENT	v_f (FIBRE VOLUME FRACTION)	DENSITY	APPARENT INTERLAMINAR SHEAR STRENGTH	FLEXURAL STRENGTH	FLEXURAL MODULUS	Resin Cost[3] (€ per kg)	Resin/Hardener Mixture Cost[3] (€ per kg)
VINYLESTER	LEO SYSTEM/ LEO UD 940gsm Glass	56% (4.3%)	2.233 g/cm³ (1.8%)	44.41 MPa (8.8%)	592.0 MPa (22%)	22.03 GPa (21%)	€11.14	€14.00
URETHANE ACRYLATE	CRESTAPOL 1210/ UD 996gsm Glass[2]	57% (0.3%)	2.017 g/cm³ (0.7%)	42.09 MPa (3.0%)	790.61 MPa (11.3%)	34.52 GPa (2.0%)	€8.50	€8.46
EPOXY	PRIME 27/ UD 996gsm Glass[2]	58% (0.9%)	2.061 g/cm³ (0.5%)	58.04 MPa (2.4%)	917.1 MPa (2.4%)	35.37 GPa (2.8%)	€9.10	€10.34
	SR1125/ UD 996gsm Glass[2]	58% (3.0%)	2.198 g/cm³ (2.3%)	50.53 MPa (1.7%)	853.8 MPa (8.5%)	30.35 GPa (8.1%)	€17.60	€18.47
BIO-EPOXY	SUPER SAP CLR/ UD 996gsm Glass[2]	60% (0.6%)	2.158 g/cm³ (0.9%)	57.78 MPa (3.6%)	865.2 MPa (8.9%)	32.80 GPa (3.8%)	€10	€13.10
PHENOLIC	CELLOBOND J2027X/ UD 996gsm Glass[2]	58% (0.4%)	1.984 g/cm³ (0.9%)	33.51 MPa (4.8%)	858.8 MPa (6.7%)	34.92 GPa (4.1%)	€4.13	€4.48
THERMOPLASTIC	ELIUM/ UD 996gsm Glass[2]	56% (1.0%)	1.999 g/cm³ (0.4%)	56.87 MPa (3.6%)	942.8 MPa (3.8%)	33.86 GPa (1.6%)	€27.25	€26.83

PHASE 1 – MATERIAL CANDIDATES – Manufacturing details

RESIN CLASS	RESIN/REINFORCEMENT	RESIN : HARDENER BY WEIGHT	VISCOSITY (from datasheet)	TOOL	INFUSION TIME[4]	INFUSION TEMPERATURE	CURING SCHEDULE	POST-CURING SCHEDULE
VINYLESTER	LEO SYSTEM/ LEO UD 940gsm Glass	100 : 2	340 cP at 20°C	HEATED ALUMINIUM	20 mins	17.3°C (RT[3])	Overnight at 30°C	6 hours at 80°C
URETHANE ACRYLATE	CRESTAPOL 1210/ UD 996gsm Glass[2]	100 : 2 : 1 : 1	175 cP at 25°C	GLASS	11 mins	21.1°C (RT[3])	60 mins at RT[3]	No post-cure required
EPOXY	PRIME 27/ UD 996gsm Glass[2]	100 : 28	285 cP at 20°C 150 cP at 30°C	GLASS + HEATED MAT	15 mins	18.8°C (RT[3])	1 hour at 45°C Overnight at RT[3]	7 hours at 65°C
EPOXY	SR1125/ UD 996gsm Glass[2]	100 : 14	680 cP at 20°C 305 cP at 30°C 160 cP at 40°C	GLASS + HEATED MAT	40 mins	19.9°C (RT[3])	16 hours at 40°C	8 hours at 80°C
BIO-EPOXY	SUPER SAP CLR/ UD 996gsm Glass[2]	100 : 33	300 cP at 25°C	HEATED ALUMINIUM	92 mins	35°C	Overnight at RT[3]	2 hours at 120°C
PHENOLIC	CELLOBOND J2027X/ UD 996gsm Glass[2]	100 : 4	270 cP at 25°C	HEATED ALUMINIUM	36 mins	60°C	15 mins at 60°C	3 hours at 80°C
THERMOPLASTIC	ELIUM/ UD 996gsm Glass[2]	100 : 2.5	100 cP at 25°C	GLASS	23 mins	21.9°C (RT[3])	Overnight at RT[3]	No post-cure required

FIBRESHIP

PHASE 1 – MATERIAL CANDIDATES – DEFINITION OF A CRITERIA FOR MATERIAL DOWN-SELECTION

	Mechanical Properties (Dry Condition)			Manufacturing				Impact				Total Score / Rank
Weight /100	35			35				30				
	ILSS[1]	Flexural Strength[2]	Flexural Stiffness[3]	Elevated Temp infusion/ cure[4]	Post Cure[5]	Infusion Time[6]	No. of resin system Components[7]	Cost[8]	Claimed FR[9]	Styrene[10]	Recyclability[11]	
Weight	/15	/10	/10	/10	/10	/10	/5	/10	/10	/5	/5	
Leo system	10	3	3	0	0	5	5	5	10	0	0	41 (6)
Crestapol 1210	10	6	6	10	10	10	0	5	0	0	0	57 (2)
Prime 27	15	6	10	0	0	10	0	5	0	5	0	51 (4)
SR1125	10	6	6	0	0	5	5	5	10	5	0	52 (3)
SUPER SAP CLR	10	6	6	0	0	0	5	5	0	5	0	37 (7)
CELLOBOND	5	6	6	0	0	0	5	10	10	5	0	47 (5)
ELIUM	10	10	6	10	10	5	5	0	0	5	5	66 (1)

Notes:

	Criteria		Relative Scoring
1	ILSS (Interlaminar shear strength)	Interlaminar shear strength established from short beam shear test	Highest 15 | all others 10 | Lowest 5
2	Flexural Strength	Flexural Strength established from 3-point bend test	Highest 10 | all others 6 | Lowest 3
3	Flexural Modulus	Flexural Modulus established from 3-point bend test	Highest 10 | all others 6 | Lowest 3
4	Elevated Temperature infusion and or cure requirement	As specified by resin supplier. Certain resin systems require elevated temperature curing to achieve full mechanical properties / to achieve a specified glass transition temperature	10 (Elevated temperature Not Required) | 0 (Required)
5	Elevated Temperature Post Cure Requirement	As specified by resin supplier. Certain resin systems require elevated temperature postcure to achieve full mechanical properties / to a achieve specified glass transition temperature	10 (Post Cure Not Required) | 0 (Required)
6	Infusion Time	Time required to fully infuse a flat panel as recorded during laboratory infusion trials	10 (≤ 15 mins) | 5 (>15&≤ 35 mins) | 0 (> 35 mins)
7	No. of Components required	Number of components in resin system (resin, catalyst, initiator etc.)	5 (2 part resin system) | 0 (> 2 part resin system)
8	Cost	Cost of samples as purchased by ULim	Lowest 10 | all others 5 | Highest 0
9	Claimed Fire Retardancy	Fire retardancy as claimed by resin supplier	10 (Yes) | 0 (No)
10	Styrene	Resins based on styrene reactive diluent technology (e.g. polyester/vinylester/urethane acrylate) present issues with styrene emissions/migration, and manufacturing personnel exposure	5 (No styrene content) | 0 (Contains styrene)
11	Recyclability	Thermoplastic resins can be reformed on heating and as such have a high potential for recycling | Thermosetting resins can not be reformed on heating and are inherently difficult to recycle	5 (Thermoplastic resin) | 0 (Thermosetting resin)

1st draft ranking: (1) Elium |(2) Crestapol 1210 |(3) SR1125

PHASE 1 – MATERIAL CANDIDATES – DEFINITION OF A CRITERIA FOR MATERIAL DOWN-SELECTION

	Mechanical Properties (Dry Condition)			Manufacturing				Impact				Total Score /110	
Weight	20			50				40					
	ILSS[1]	Flexural Strength[2]	Flexural Stiffness[3]	Elevated Temp infusion/ cure[4]	Post Cure[5]	Infusion capability[6]	Worldwide knowledge (possibility to be used worldwide)	Cost[8]	Claimed FR[9]	Worker health impact[10]	Recyclability[11]		
Weight	/10	/5	/5	/10	/10	/20	/10	/15	/21	/2	/2		
Synolite 8488 G-2	?	?	?	10	10	20	10	15	0	1	1	67	To be completed
DION 9102-683				10	10	20	10	13	0	1	?	64	
Leo system	7	1.5	1.5	5	0	14	10	12	21	1	0	73	System to be checked with Saertex
Crestapol 1210	7	3	3	10	10	20	0	7	0	1	0	61	
Prime 27	10	3	5	5	0	12	5	10	0	1	0	51	
SR1125	7	3	3	5	0	12	5	8	21	1	0	65	
SUPER SAP CLR	7	3	3	0	0	6	5	7	0	1	0	32	OUT due to high infusion T°
CELLOBOND	4	3	3	0	0	6	0	15	21	0	0	52	OUT due to high infusion T° and gel time too short
ELIUM	7	5	3	10	10	12	0	0	0	2	1	50	

Traction strenght ?

This item has changed

Ranking if FR is an option	1st Leo System, 2nd SR 1125
Ranking if FR is not an option	1st Leo System, 2nd Synolite 8488 G-2 / DION 9102-683, 3rd SR 1125

Previous ponderation values

35(15/10/10) 35(10/10/10/5) 30(10/10/5/5)

TESTING CAMPAIGN – 2ND PHASE

PHASE 2 – MATERIAL DETAILED MATERIAL CHARACTERIZATION

SR1125

X3 material systems

Evaluate SR1125 with various reinforcements: Carbon, Basalt, Glass

MATERIALS:	• SR1125 / Glass (Completed) • SR1125 / Basalt • SR1125 / Carbon
OUTPUTS:	• Interlaminar shear strength • Flexural Strength • Flexural Stiffness • Density • Fibre volume fraction

Down-select > Move forward with a single reinforcement

X1 material system

Establish Tensile and Flexural properties of SR1125 with one down-selected reinforcement

MATERIALS	• SR1125 with Glass OR Carbon OR Basalt
OUTPUTS	• Tensile Strength • Tensile Modulus • Flexural Strength • Flexural Modulus • Fibre volume fraction

Sandwich Panel Manufacture and Evaluation (SR1125 with one down-selected reinforcement)

OUTPUTS	• Flexural Strength • Flexural Modulus

Fatigue testing (ASTM D3479) of SR1125

LEO SYSTEM

Move forward with LEO compatible glass reinforcement only

X1 material system

Establish Tensile and Flexural properties of LEO SYSTEM with LEO Glass

MATERIALS	• LEO SYSTEM with LEO Glass
OUTPUTS	• Tensile Strength • Tensile Modulus • Flexural Strength • Flexural Modulus • Density • Fibre volume Fraction

Sandwich Panel Manufacture and Evaluation (LEO SYSTEM)

OUTPUTS	• Flexural Strength • Flexural Modulus

Fatigue testing (ASTM D3479) of LEO SYSTEM

TESTING CAMPAIGN – 2ND PHASE

Comparison of fibre properties

RESIN CLASS	RESIN	REINFORCEMENT	Reinforcement Cost	FIBRE VOLUME FRACTION	DENSITY*	APPARENT INTERLAMINAR SHEAR STRENGTH	FLEXURAL STRENGTH	FLEXURAL MODULUS
Epoxy	SR 1125	Glass fibres SAERTEX U-E-996g/m2	2.00 €/m²	53% (1.3%)	1.842 g/cm (1.9%)	50.53 MPa (1.7%)	853.8 MPa (8.5%)	30.35 GPa (8.1%)
		Carbon fibres Saertex U-C-314g/m2	10.50 €/m²	51% (1.6%)	1.371 g/cm (2.5%)	51.25 MPa (8.4%)	798.8 MPa (± 8.5%)	74.43 GPa (± 10.2%)
		Basalt fibres Basaltex BAS UNI 350	5.95 €/m²	32% (3.9%)	1.655 g/cm (1.2%)	40.63 MPa (3.7%)	577.9 MPa (4.2%)	22.72 GPa (4.1%)

DRY VS WET Results

RESIN CLASS	RESIN/ REINFORCEMENT	APPARENT INTERLAMINAR SHEAR STRENGTH			FLEXURAL STRENGTH			FLEXURAL MODULUS		
		DRY	WET*	CHANGE	DRY	WET*	CHANGE	DRY	WET*	CHANGE
STAGE 2 VINYL ESTER	LEO INFUSION RESIN/LEO UD 940gsm Glass	38.11 MPa (4.9%)	37.48 MPa (3.4%)	-1.7%	820.71 MPa (6.8%)	829.22 MPa (9.8%)	+1.0%	28.59 GPa (4.0%)	31.69 GPa (2.1%)	+10.8%
STAGE 2 EPOXY	SR1125/ UD 996gsm Glass	50.53 MPa (1.7%)	51.86 MPa (1.7%)	+2.6%	853.8 MPa (8.5%)	812.2 MPa (1.9%)	-4.9%	30.35 GPa (8.1%)	31.02 GPa (2.7%)	+2.2%

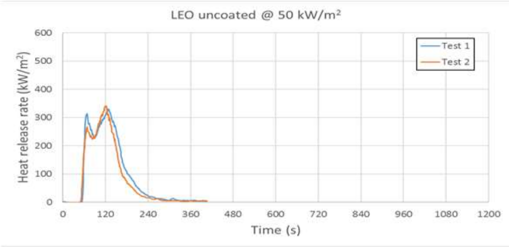
*WET SAMPLES ARE SOAKED IN DEIONISED WATER FOR 28 DAYS AT 35°C

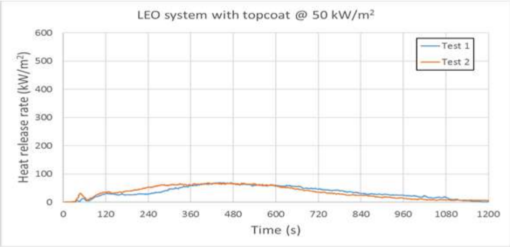
FIRE PERFORMANCE

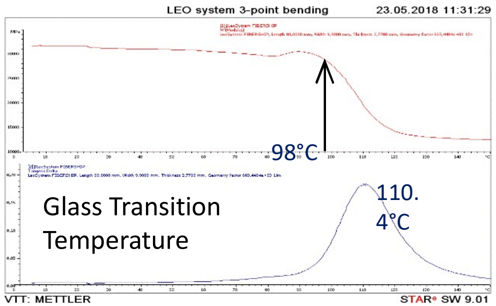
- Fire performance is of utmost importance for Fibreship application and has been a key point for phase 1 and phase 2 material selection. Tests where made in materials w/o coatings.

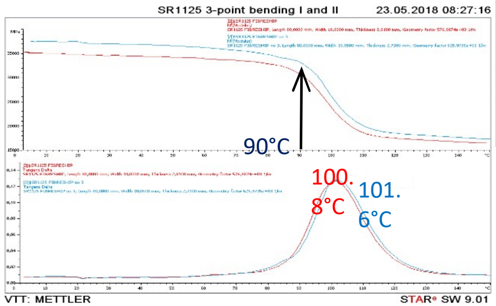
TGA = Thermogravimetric Analysis
MCC = Micro-scale Combustion Calorimetry
DMTA = Dynamic Mechanical Thermal Analysis
DSC = Differential Scanning Calorimetry
TPS = Transient Plane Source

TEST METHOD	PHASE	OUTCOME
Cone calorimeter	1 & 2	time to ignition, heat release and smoke production data per unit area, mass loss
TGA	1	mass loss as a function of temperature
MCC	2	heat release as a function of temperature
DMTA	2	temperature dependency of key mechanical properties (storage modulus, loss modulus), glass transition temperature
DSC	2	specific heat capacity
TPS	2	thermal conductivity









FIRE PERFORMANCE

Resins considered and results obtained from the CC test during the first phase analysis

Cone calorimeter test sample

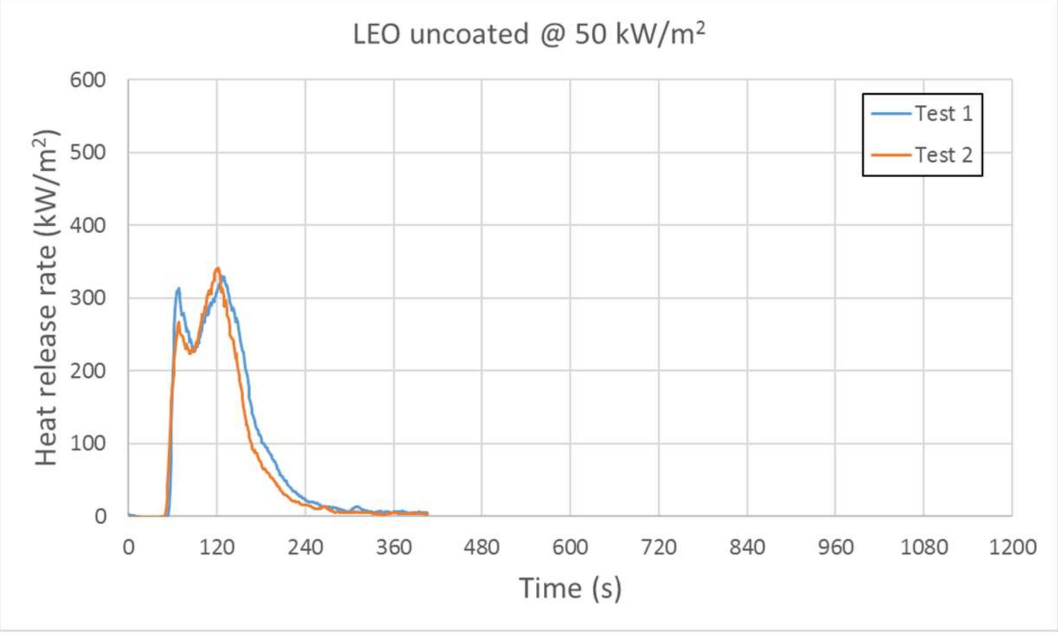
RESIN CLASS	RESIN DETAILS	t_{ig} (s)	HRR_{max} (kW/m²)	THR (MJ/m²)	TSP (m²)
Vinylester	LEO system with topcoat	75	69	42.3	8.8
	LEO without topcoat	50	336	33.5	15.1
Urethane acrylate	Crestapol 1210	44	314	35.4	9.3
Epoxy	Prime 27	60	496	39.4	10.7
	SR1125 with topcoat	53	261	40.7	9.3
	SR1125 without topcoat	53	546	42.5	13.5
Bio-epoxy	Super Sap CLR	61	520	42.0	12.0
Phenolic	Cellobond J2027X	*)	71	9.9	0.4
Thermoplastic	Elium	23	255	40.7	1.8

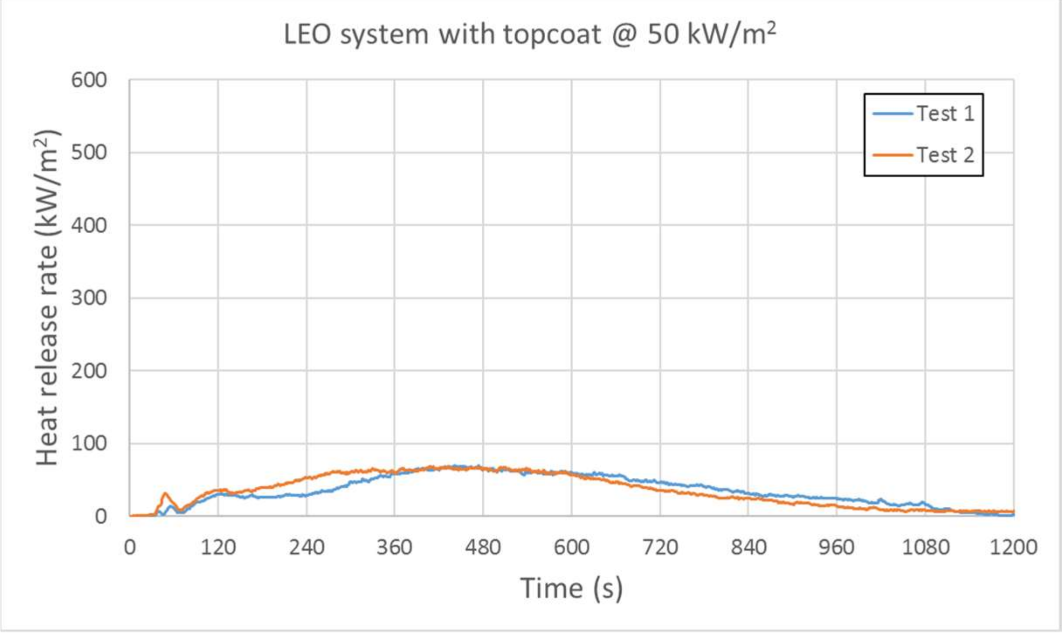
*) Exceptional ignition behaviour: small local flame in ca. 90 s, 50 % of area ignited in ca. 120 s, whole surface ignited in ca. 180 s

FIRE PERFORMANCE

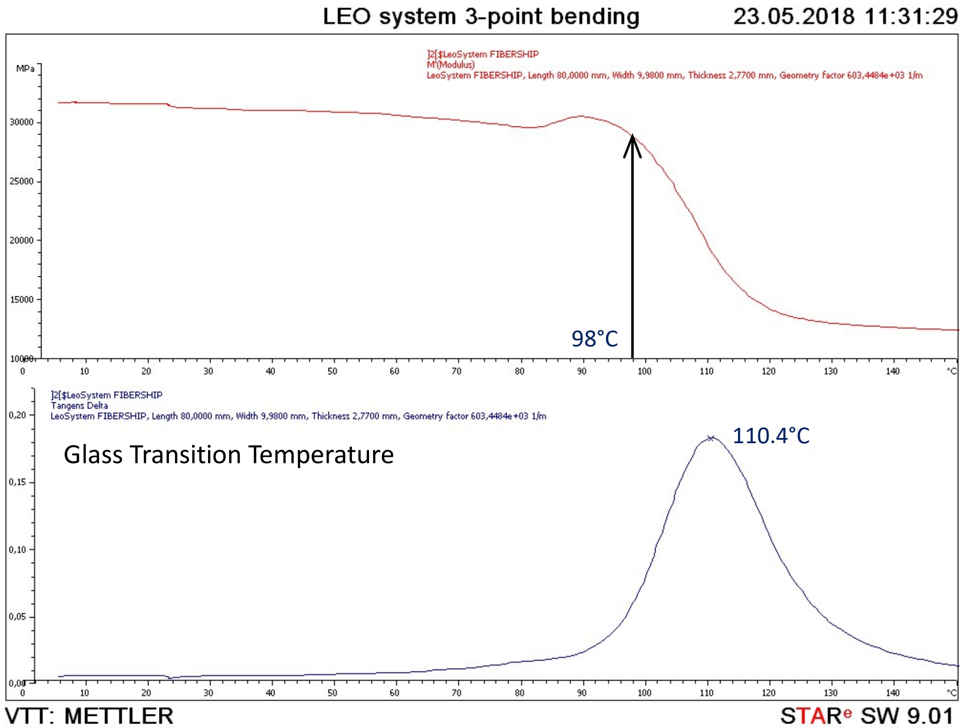
EXAMPLES OF THE RESULTS OBTAINED IN THE FIRST PHASE – LEO SYSTEM

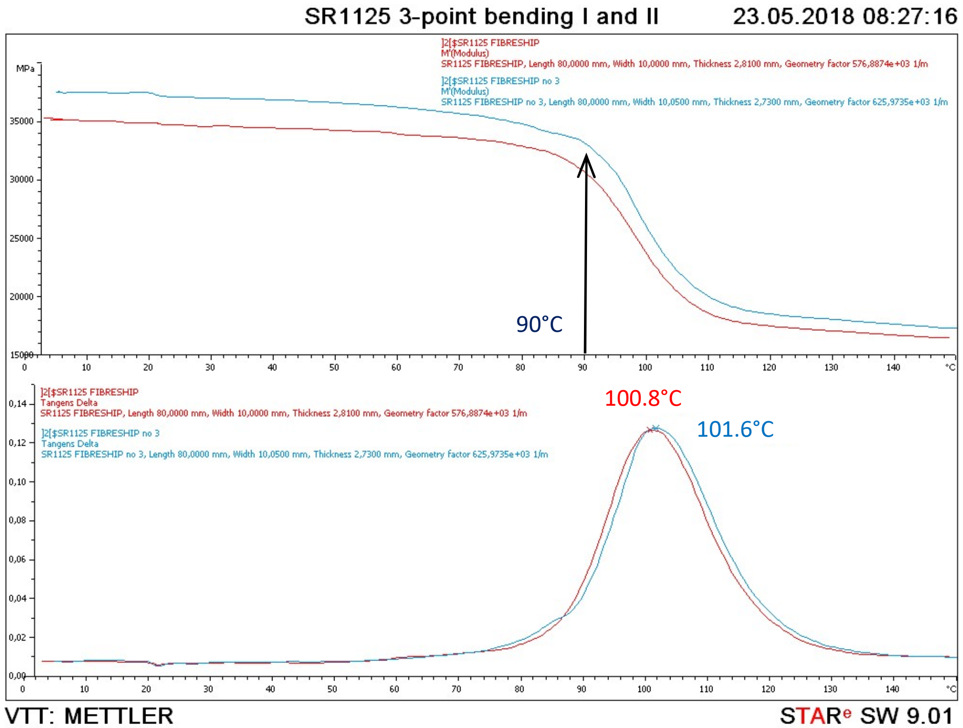
HEAT RELEASE RATE:





EXAMPLES OF THE RESULTS OBTAINED IN THE SECOND PHASE – DMTA Results





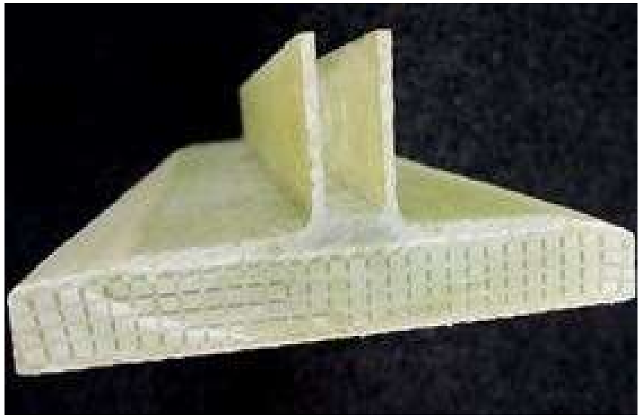
Storage modulus (in MPa) and loss factor (tangens delta) values as the function of temperature with 1 Hz frequency measured in three point bending.

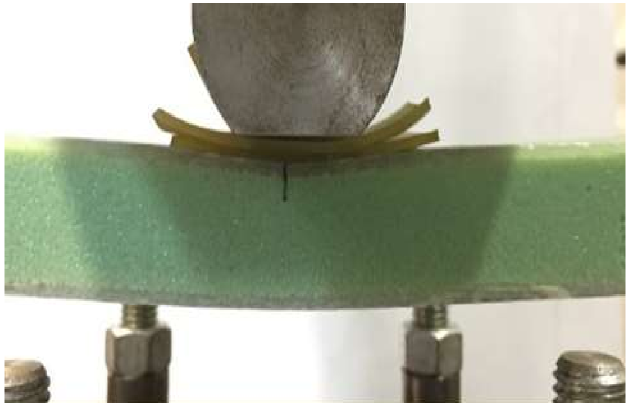
CHARACTERIZATION AND SIMULATION OF FIBRE-BASED MATERIALS

MODEL TO ANALYZE THE MECHANICAL PEFORMANCE OF COMPOSITES

INTRODUCTION. Challenges with composites

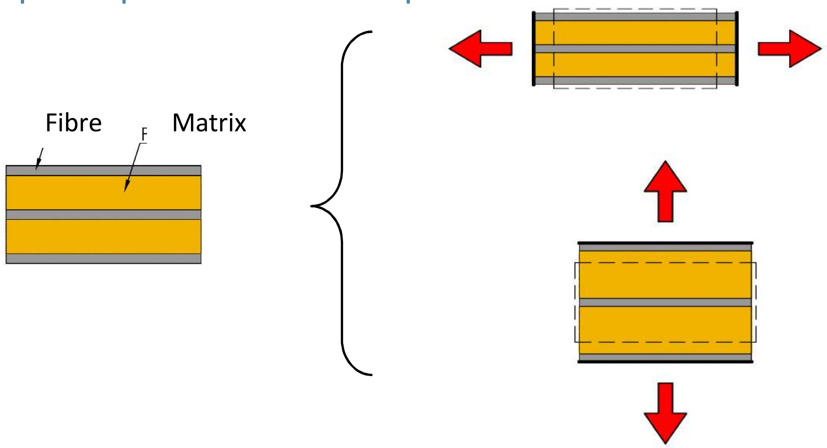
- Different materials, with different mechanical performance, are coupled providing combined response
- Anisotropic behaviour: material properties are orientation-dependency.
- Different and complex failure modes (delamination, matrix cracking, fibre breakage,…)
- Lack of experimental data compared with other materials.





Numerical models for composite material characterization will be based on the serial/parallel mixing theory, which acts as constitutive equations manager, providing the non-linear response of the composite by coupling the constitutive equations of its components.

It assumes that the contribution of each component to the composite performance is proportional to its volumetric participation in the composite.



Parallel behavior

$\varepsilon_1 = \varepsilon_2 = \ldots = \varepsilon_n$

$$\begin{cases} {}^{c}\varepsilon_P = {}^{m}\varepsilon_P = {}^{f}\varepsilon_P \\ {}^{c}\sigma_P = {}^{m}k\,{}^{m}\sigma_P + {}^{f}k\,{}^{f}\sigma_P \end{cases}$$

Serial behavior

$\sigma_1 = \sigma_2 = \ldots = \sigma_n$

$$\begin{cases} {}^{c}\varepsilon_S = {}^{m}k\,{}^{m}\varepsilon_S + {}^{f}k\,{}^{f}\varepsilon_S \\ {}^{c}\sigma_S = {}^{m}\sigma_S = {}^{f}\sigma_S \end{cases}$$

COMPATIBLITY EQUATIONS

Classic RoM

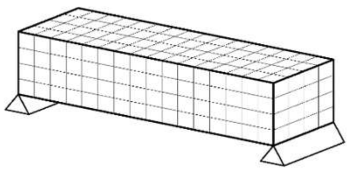
$${}^{c}\sigma = {}^{f}k \cdot {}^{f}\sigma + {}^{m}k \cdot {}^{m}\sigma$$

S/P RoM

$${}^{i}\sigma = \frac{\partial \Psi^{i}}{\partial \varepsilon^{i}} \longrightarrow {}^{c}\sigma = {}^{f}k \cdot \frac{\partial \Psi^{f}}{\partial \varepsilon^{f}} + {}^{m}k \cdot \frac{\partial \Psi^{m}}{\partial \varepsilon^{m}}$$

MODEL TO ANALYZE THE MECHANICAL PEFORMANCE OF COMPOSITES

Implementation of the serial/parallel mixing in a code based on the Finite Element Method



$$K \cdot D = F$$

$$\varepsilon = B : D$$

$$\sigma = C : \varepsilon$$

Or non-linear constitutive equation

$$\sum F_{int} \overset{¿?}{=} \sum F_{ext}$$

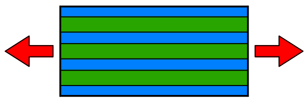
$$\varepsilon_c = \begin{cases} \varepsilon_f \\ \varepsilon_m \end{cases} \qquad \begin{aligned} \varepsilon_f &\longrightarrow \sigma_f = C_f : \varepsilon_f \\ \varepsilon_m &\longrightarrow \sigma_m = C_m : \varepsilon_m \end{aligned}$$

Or non-linear constitutive equation

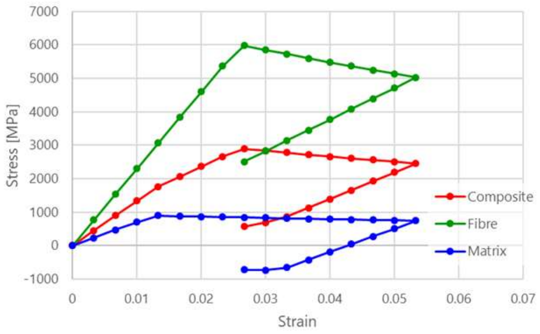
$$\longrightarrow \begin{cases} \varepsilon_f^P = \varepsilon_m^P \\ \sigma_f^S = \sigma_m^S \\ \sigma_c = k_f \cdot \sigma_f + k_m \cdot \sigma_m \end{cases}$$

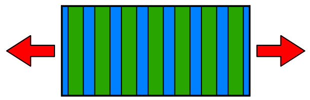
MODEL TO ANALYZE THE MECHANICAL PEFORMANCE OF COMPOSITES

FORMULATION PERFORMANCE:

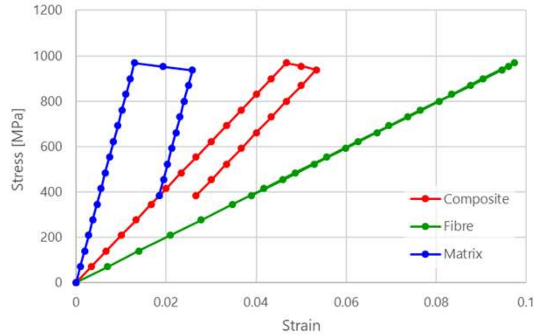


Stress-Strain in load direction

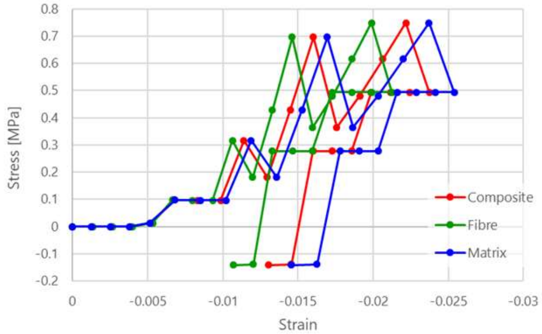




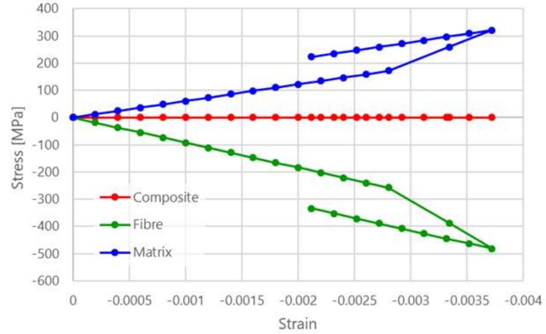
Stress-Strain in load direction



Stress-strain perpendicular to load



Stress-strain perpendicular to load



MODEL TO ANALYZE THE MECHANICAL PEFORMANCE OF COMPOSITES

- With this formulation the composite performance is obtained from the mechanical parameters of the composite components.
- Failure is predicted by the components failure, instead of a failure criteria that considers the composite a material by itself.

CALIBRATION PROCESS – PARAMETERS REQUIRED

From composite:

Each different ply orientation, Volumetric participation of each ply with different orientation, Fiber/Matrix system

From constituent materials:

Young modulus, Poisson coefficient, Shear modulus, Volumetric participation, Non-linear parameters (strengths, fracture energy)

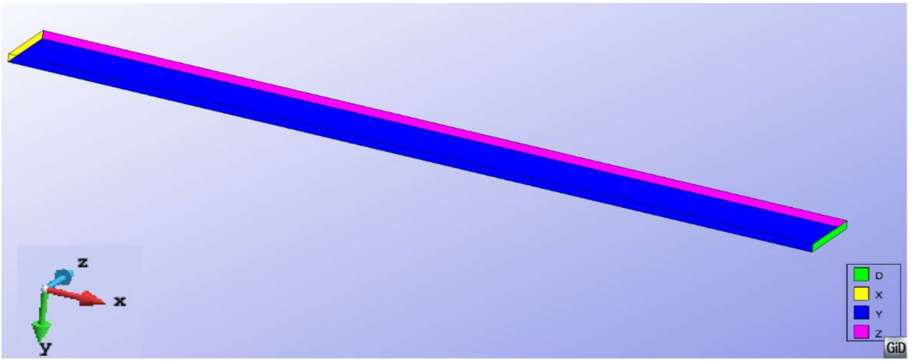
MATERIAL PROPERTIES DEFINED (FROM CALIBRATION PROCESS)

Elastic properties			
Material	Young Modulus (Gpa)	Poisson coefficient	Shear Modulus (Gpa)
Leo Fiber E-Glass	70	0.22	1.66
Leo Vinyl Ester	3	0.3	0.455

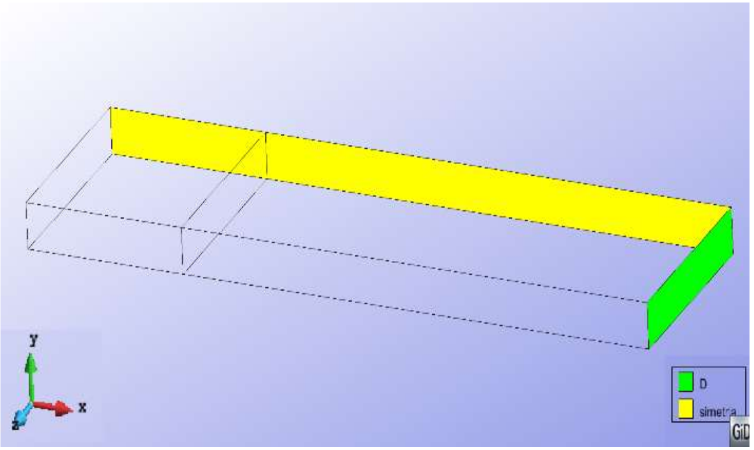
Non-Linear properties					
Material	Yield criteria	Constitutive law	Compressive threshold strength (MPa)	Shear strength (MPa)	Fracture energy (J/m2)
Leo Fiber Glass	Norm principal stress	Exponential damage	1400	1400	185000
Leo Vinyl Ester	Norm principal stress	Exponential damage	120	70.6	5370

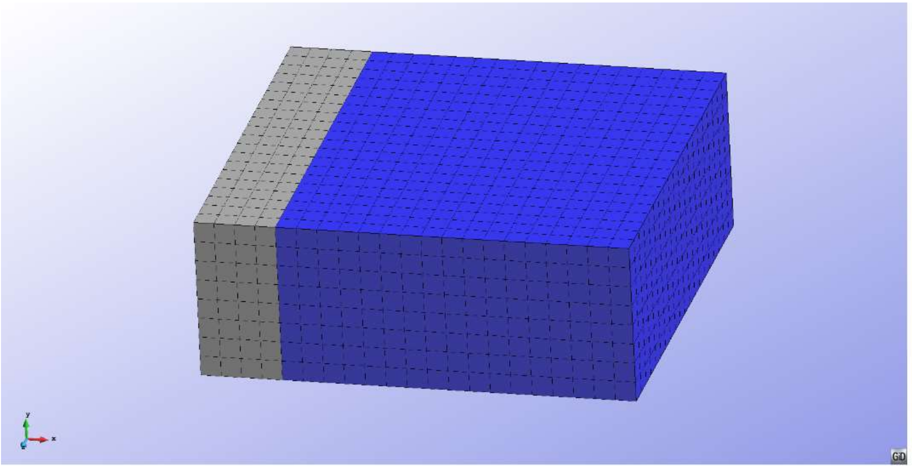
RESULTS. Numerical model

Tensile test model



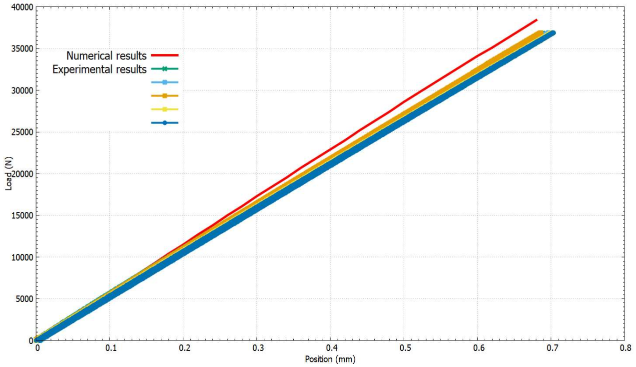
Flexure test model



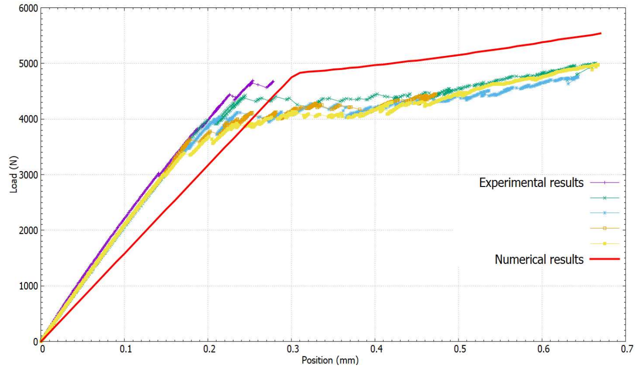


Shear test model

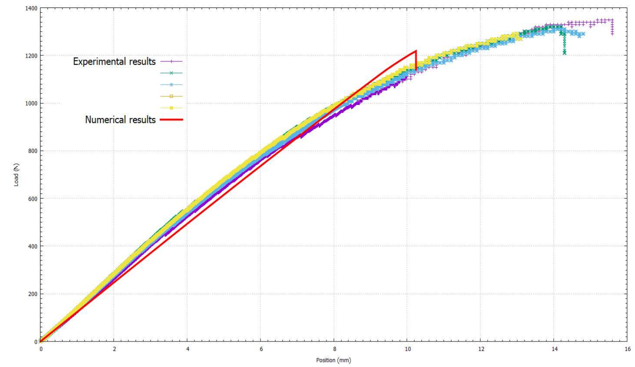
COMPARISION OF NUMERICAL VS EXPERIMENTAL RESULTS FOR GF/VINYLESTER LEO SYSTEM



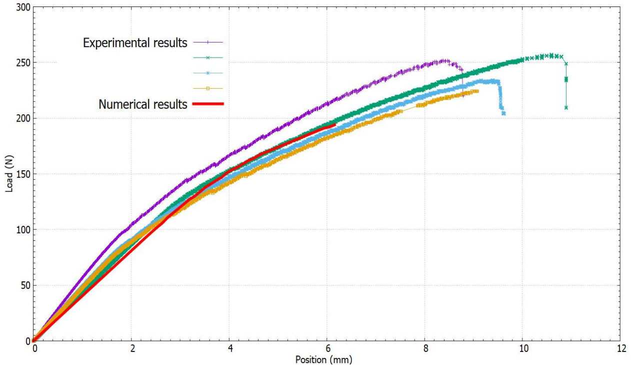
Longitudinal tensile test



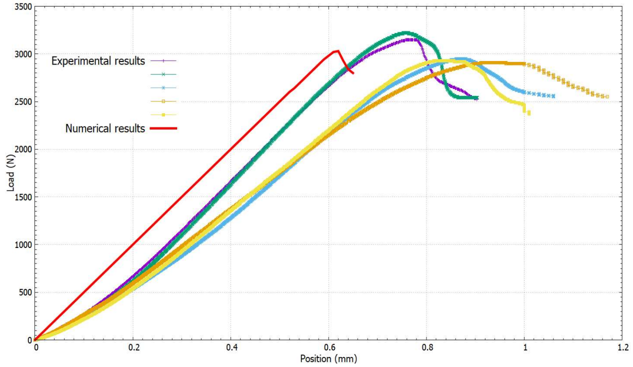
Transversal tensile test



Longitudinal flexure test



Transversal flexure test

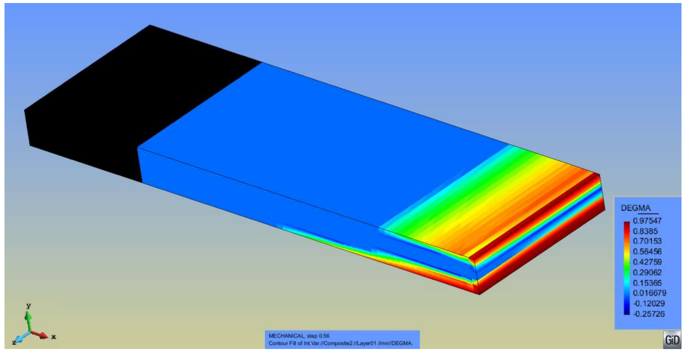


Shear test

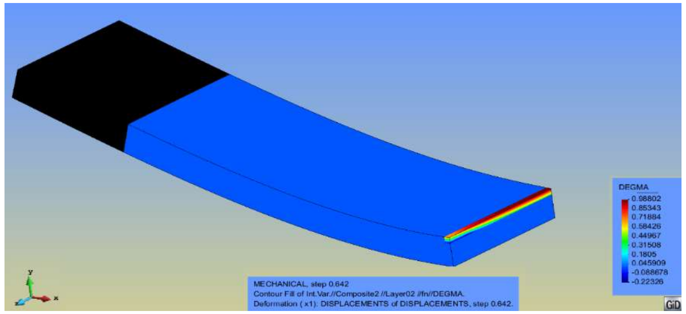
RESULTS FEM MODEL. Failure modes.

A numerical simulation not only has to represent the global performance correctly, besides has to show the equivalent failure mechanism

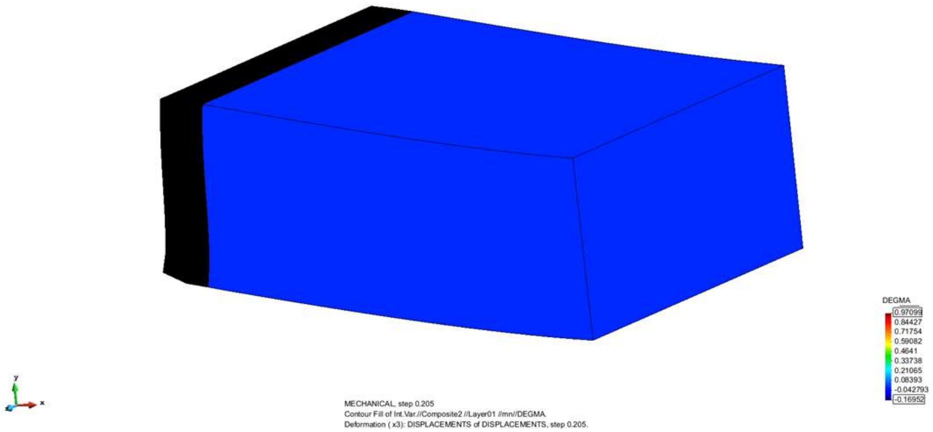
3P Bending in fibre direction



3P Bending perpendicular to fibre direction

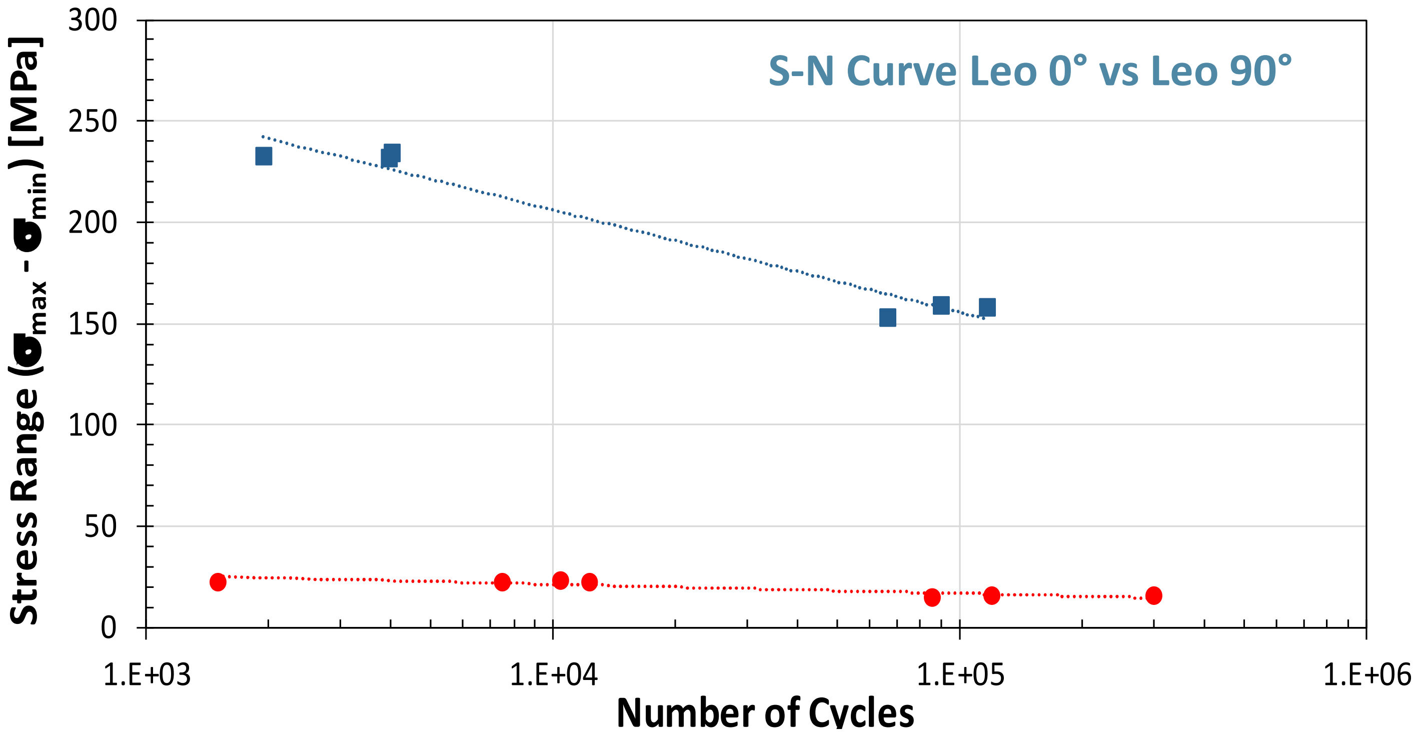


Shear test



Fatigue analysis is basic in naval structures and must be also considered in composites.

Fatigue performance of composites is highly anisotropic, due to the differential fatigue performance of fibres and matrix:



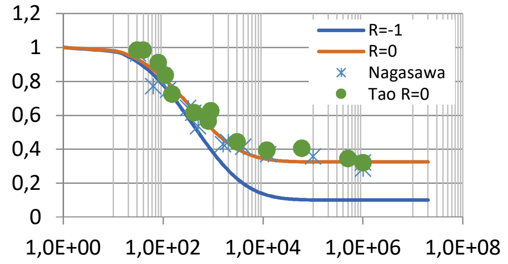
FATIGUE ANALYSIS

ADAPTATION OF THE FORMULATION TO COMPOSITES

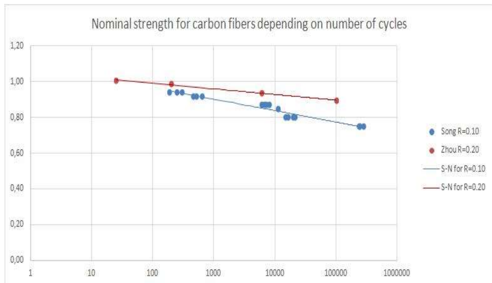
- Require to establish fatigue models for fibre and matrix.
- S/P Mixing Theory couples both materials to obtain fatigue behaviour of composite.
- **Fibre and matrix performance, both static and fatigue, are obtained by tests on UD laminates**.
    - UD loaded at longitudinal direction has a fibre-dominated performance.
    - UD loaded at transverse direction has a matrix-dominated performance.
- Failure of the laminate is supposed when damage appears on fibre for longitudinal ply.

FATIGUE MODELS

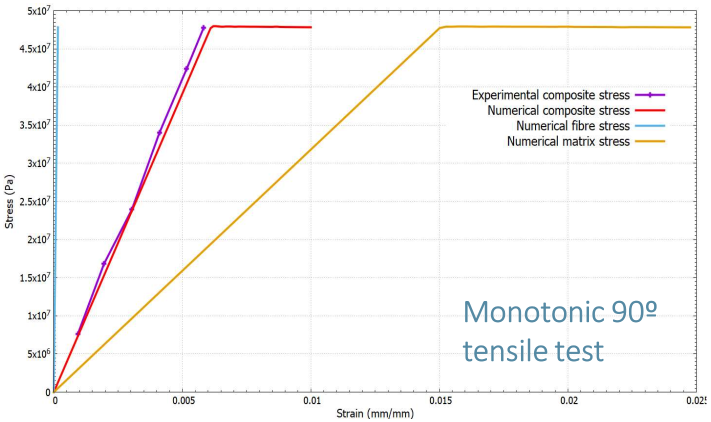
Constitutive law for matrix

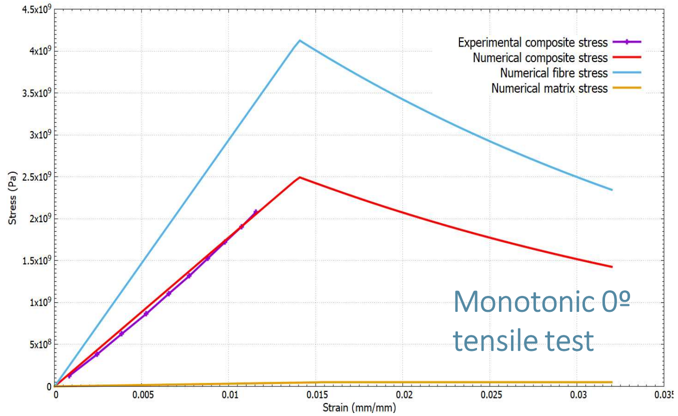


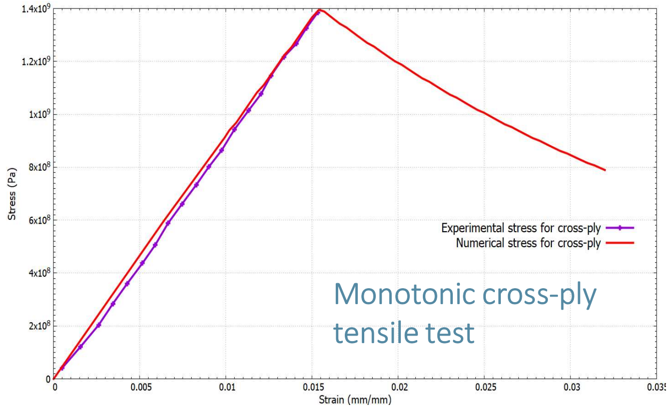
Constitutive law for fibers

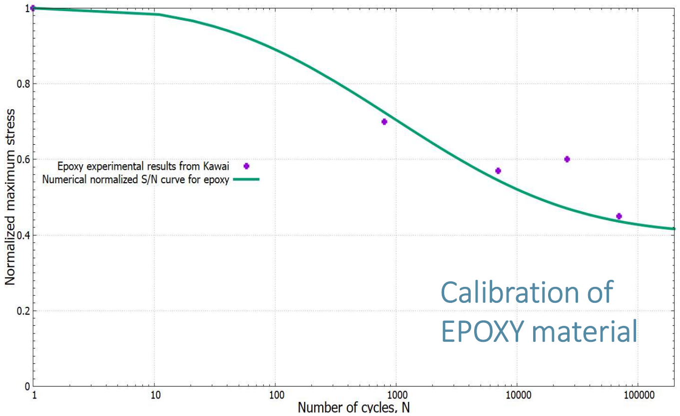


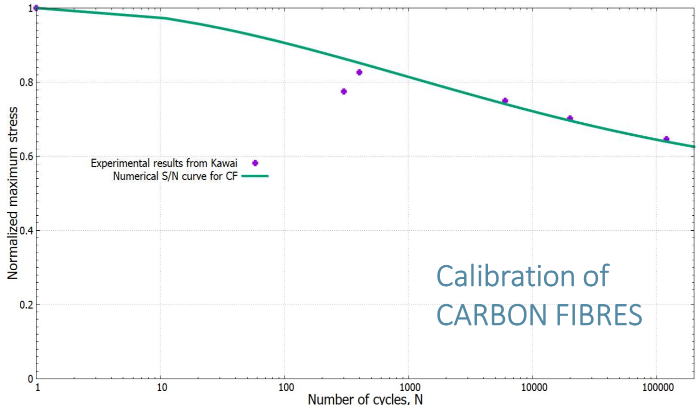
VALIDATION OF THE FORMULATION

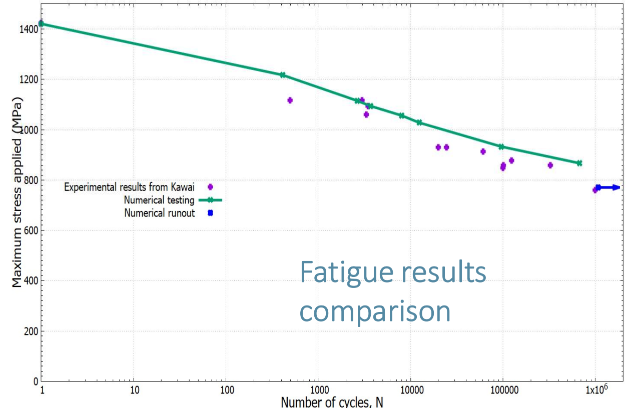






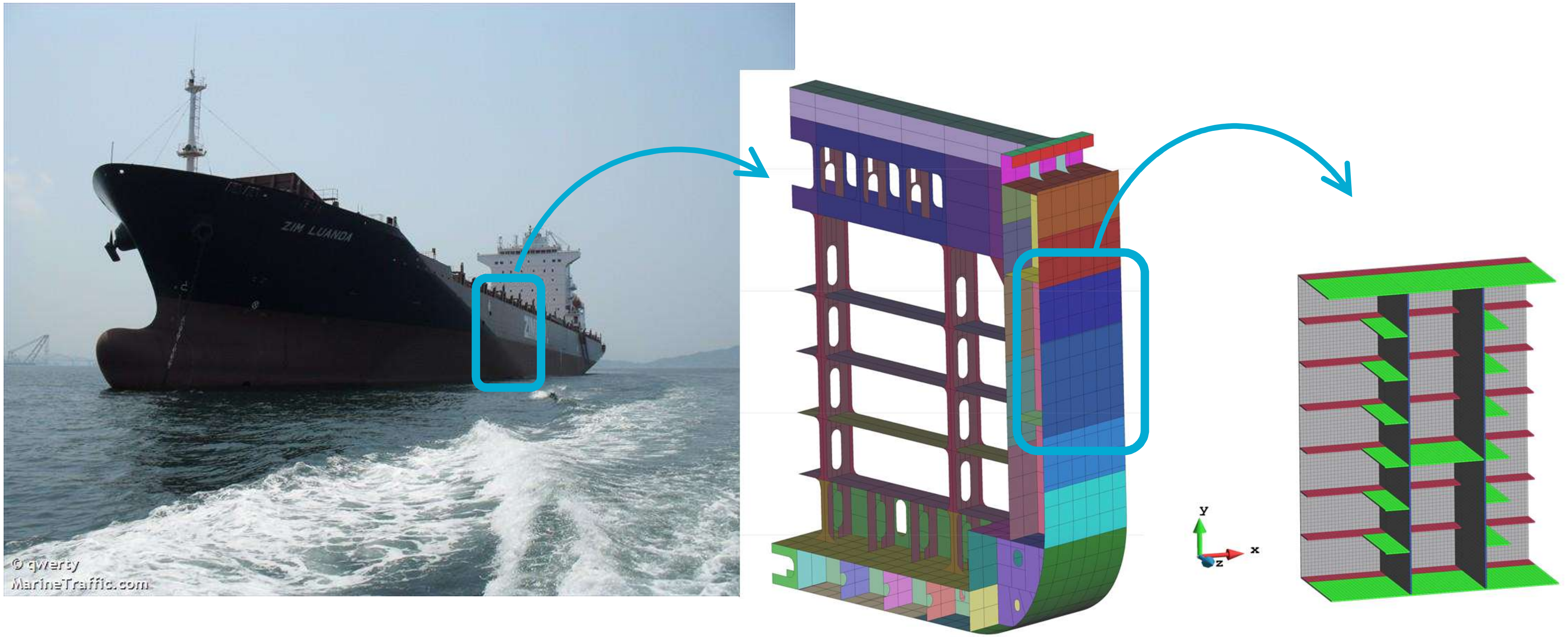






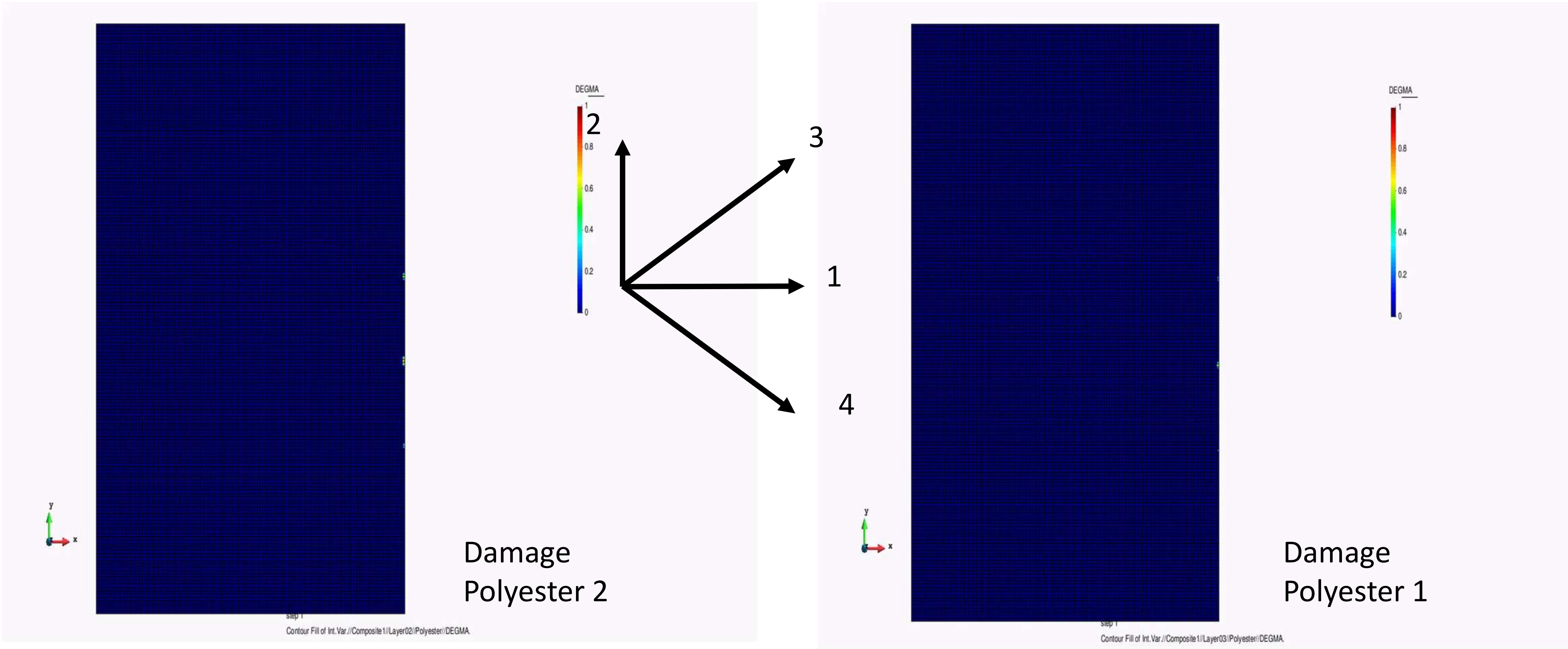
FATIGUE ANALYSIS

The procedure developed is applied to the Zim Luanda container ship vessel



Fatigue analysis

Cycle jumps: 1, 25.000, 150.000, 225.000 cycles.



THANK YOU

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